Comment on "Observation of Collective Modes of Ultracold Plasmas"

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In the work [1] Fletcher *et al.* reported on the new interesting phenomenon in ultracold plasmas—the observation of subharmonics of the electron emission from the expanding plasma clouds under their irradiation by the external radiowaves (in addition to the basic plasmon harmonic detected in the earlier works). Unfortunately, a theoretical interpretation of the additional harmonics remained doubtful.

The authors of the experiment assumed that the subharmonics were the so-called Tonks–Dattner resonances—the standing waves of the electron plasma oscillations arising due to the thermal term in the Bohm–Gross dispersion relation. Such interpretation, however, encounters a number of obstacles. One of them was mentioned already in the original paper [1]: this is the lack of the adequate boundary conditions for the formation of standing waves in the unbounded gaseous cloud.

The second problem, which may be even more important, is the temperature dependence of the observed subharmonics. If they are produced by a thermal term in the dispersion relation, the pattern of subpeaks in Fig. 1 [1] should be more pronounced with the increase in the electron temperature and, therefore, decrease in the neutrality of the plasma cloud (due to escape of the most energetic electrons). This seems to be in conflict with the experimental finding that "the largest number of peaks are found at the highest densities and neutralities".

The aim of the present comment is to mention that a more promising interpretation of the observed phenomenon might be based on the ionization of secondary Rydberg atoms, formed during expansion and cooling of the plasma cloud. This idea is well supported, particularly, by a close similarity between the subharmonics of electron emission presented in Fig. 1 of paper [1] and in Fig. 3 of the work by Maeda and Gallagher [2], where no plasma effects were involved at all.

In the last-cited experiment, the atoms were excited to the specified Rydberg states, and it was found that the efficiency of their subsequent ionization by microwave (MW) irradiation shows a number of peaks in the interval of the scaled frequency $\Omega \equiv \omega/\omega_{\rm K} \approx 0.5\div2$, where ω is the MW frequency, and $\omega_{\rm K}$ is the Keplerian frequency of the atom. On the other hand, in the experiment with plasma clouds [1] there should be formation of the secondary Rydberg atoms due to three-body recombination during the cloud expansion and cooling. The typical radii of such atoms are initially just about the average electron–ion separation in plasma (Wigner–Seitz radius) $r_{\rm WS} \approx (2N)^{-1/3}$, where N is the concentration of charged particles; and their Keplerian frequencies should be $\omega_{\rm K} \equiv e/\big(m_e^{1/2} r_{\rm WS}^{3/2}\big) \approx \sqrt{2}\, e\, m_e^{-1/2} N^{1/2}$. This quantity almost coincides with a plasmon frequency for the spherical cloud, which is the standard Langmuir frequency $\omega_{\rm L} \equiv 2\sqrt{\pi}\, e\, m_e^{-1/2} N^{1/2}$ reduced by the factor $2\div3$, depending on the particular density distribution inside the cloud.

Therefore, the pattern of subharmonics observed in the ultracold plasma experiment [1] might be a combination of the basic plasmon oscillation (which should definitely exist) and a number of peaks in the ionization efficiency of the secondary Rydberg atoms. The peaks occur at the various values of $\omega/\omega_{\rm K}$, when concentration N changes in the course of the plasma cloud expansion. Such interpretation avoids the problem of adequate boundary conditions for the formation of standing waves and gives a correct dependence on the plasma parameters (the secondary Rydberg atoms should be formed more efficiently at the lower electron temperature and, consequently, the higher plasma neutrality).

It is important to mention also that the oscillatory structure of the ionization efficiency in the study by Maeda and Gallagher was especially pronounced when the ionization potential was artificially decreased (*e.g.* curves for the threshold principal quantum numbers $n_c =$ 145 and 120 in Fig. 3 [2]). And essentially the same situation took place in the experiment by Fletcher *et al.* [1], where the ionization threshold was decreased just due to the finite separation between the plasma particles.

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[2] H. Maeda and T. F. Gallagher, Phys. Rev. Lett. **93**, 193002 (2004).